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EXPERIENCE TESTING ENERGYPLUS WITH THE IEA HVAC BESTEST E100-E200 SERIES

Robert H. Henninger[1], Michael J. Witte[1], and Drury B. Crawley[2]
[1]GARD Analytics, Inc., Park Ridge, Illinois, USA
[2] U.S. Department of Energy, Washington, DC, USA

ABSTRACT

The EnergyPlus building energy simulation software has been tested using the IEA HVAC BESTEST E100-E200 series of tests. The Volume 1 final report for the International Energy Agency (IEA) Building Energy Simulation Test and Diagnostic Method for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST), was recently published in January 2002. HVAC BESTEST is a series of steady-state tests for a single-zone DX cooling system. Cases range from dry to wet coil, low to high part load, and low to high temperatures. This published test suite includes three sets of analytical solutions and results from several other simulation programs for comparison.

This test suite was initially used to test EnergyPlus beginning with beta versions prior to its official public release, and it is also applied as an ongoing quality assurance test. The application of these tests proved to be very useful in several ways:

- Revealed input model shortcomings, which resulted in new user inputs being added.
- Revealed reporting errors which were fixed.
- Revealed algorithmic errors which were fixed.
- Revealed algorithmic shortcomings which were improved or eliminated through the use of more rigorous calculations for certain components.
- In later versions, caught newly introduced bugs before public release of updates.

Overall, the application of this test suite has been extremely useful in debugging and verifying the DX cooling algorithms in EnergyPlus. This paper summarizes the difficulties encountered and the benefits gained in applying the tests.

INTRODUCTION

The International Energy Agency (IEA) HVAC BESTEST contains a set of analytical tests as well as a set of comparative results from seven other whole building simulation programs that participated in the IEA project. Analytical tests compare a program's results to mathematical solutions for simple cases. This is an excellent method to use for assessing the accuracy of results since there is only one solution for the case analyzed given the boundary conditions. Comparative tests compare a program to itself or to other simulation programs. Both types of testing accomplish results on two different levels, both validation and debugging. Validation is accomplished when the results of the test program compare favorably with the analytical results. Debugging is accomplished when the results for certain cases do not compare favorably with the analytical results and then through systematic checking it is determined that the source of the difference is due to an input error, a modeling inconsistency or flaw in the program logic.

The tests described in International Energy Agency (IEA) Building Energy Simulation Test and Diagnostic Method for HVAC Equipment Models (HVAC BESTEST), Volume 1: Cases E100 – E200, (Neymark & Judkoff 2001) were performed. Final comparison results for all programs that participated in the IEA project are reported in an NREL report by the same name as above but with a January 2002 publish date (Neymark & Judkoff 2002).

As stated in its Introduction, the IEA HVAC BESTEST report "documents an analytical verification and comparative diagnostic procedure for testing the ability of whole building simulation programs to model the performance of unitary space cooling equipment that is typically modeled using manufacturer design data presented in the form of empirically derived performance maps. The report also includes results from simulation programs that were used for field trials of the test procedure."

SUMMARY OF TEST CASES

The following tests were performed as specified in the HVAC BESTEST User's Manual (section 1.3):

- Case E100 – Base Case Building and Mechanical System
- Additional Dry Coil Test Cases (Cases E110, E120, E130, E140)
- Humid Zone Test Cases (Cases E150, E160, E165, E170, E180, E185, E190, E195, E200)

Base Case Building and Mechanical System (Case E100)

The basic test building is a rectangular 48 m^2 single zone (8 m wide x 6 m long x 2.7 m high) with no interior partitions and no windows. The building is intended as a near-adiabatic cell with cooling load driven by user specified internal gains. For further details refer to Section 1.3.2.1 of the HVAC BESTEST User's Manual.

The mechanical system is a simple unitary vapor compression cooling system with air cooled condenser and indoor evaporator coil, 100% convective air system, no outside air or exhaust air, single speed, draw-through air distribution fan, indoor and outdoor fans cycle on/off with compressor, no cylinder unloading, no hot gas bypass, crankcase heater and other auxiliary energy are 0. There is a non-proportional-type thermostat, heat always off, cooling on if zone air temperature >22.2°C and heat extraction rate is assumed to equal the maximum capacity of the equipment for the hour's environmental conditions. For further specifications and equipment's full-load and part load performance specifications, see Section 1.3.2.2 and Tables 1-6 in the HVAC BESTEST User's Manual.

Dry Zone and Wet Zone Series (Cases E110 – E200)

The 13 other cases represent a set of fundamental mechanical equipment tests. These cases test a program's ability to model unitary space cooling equipment performance under controlled load and weather conditions. Given the underlying physical assumptions in the case definitions, there is a mathematically provable and deterministic solution for each case. The results of analytical solutions are included in the IEA/NREL report. Only the following parameters are varied to develop the remaining test cases:

- Internal sensible gains
- Internal latent gains
- Thermostat setpoint (dry-bulb)
- Outdoor dry-bulb temperature.

Weather Data

Four three-month long (January – March) TMY format weather files were provided with the test suite. The only parameter that is different for each weather file is the ambient dry-bulb temperature; all other data is the same for each weather file. Simulations for all cases were run for a three month period. The first month of the simulation period (January) served as an initialization period. The output results reported were for the second month of the simulation (February).

ENERGYPLUS MODELING METHODOLOGY AND ISSUES

With nearly any published test suite, issues and choices arise when modeling the tests with a specific software package. These issues are summarized below.

Building Envelope Construction

The specification for the building envelope indicates that the exterior walls, roof and floor are made up of one opaque layer of insulation (R=100) with differing radiative properties for the interior surface and exterior surface (ref. Table 1-4 of Volume 1). To allow the surface radiative properties to be set at different values, the exterior wall, roof and floor had to be simulated as two insulation layers, each with R=50.

HVAC System

For modeling of the simple unitary vapor compression cooling system, the EnergyPlus Window Air Conditioner model was utilized. No other direct expansion (DX) coil cooling system was available at the time that this work began, but others have been added since then. The Window Air Conditioner model consists of three modules for which specifications can be entered: DX cooling coil, indoor fan and outside air mixer. The outside air quantity was set to 0.0. The DX coil model is based upon the DOE-2.1E DX coil simulation algorithms with modifications to the coil bypass factor calculations.

The specification calls for the unitary air conditioner to have a draw-thru indoor fan. The Window Air Conditioner model in early beta versions of EnergyPlus could only model a blow-thru fan configuration. In Version 1 Build 05 and later a draw-thru configuration is also available. This limitation may have affected the latent load on the cooling coil and the compressor energy consumption in the early results (Round 1 and Round 2), but other issues were also contributing errors at that point. A draw-thru fan was modeled in Round 3 and Round 4.

The rated coefficient of performance (COP) required as input by the EnergyPlus DX coil model requires that the input power be the combined power for the compressor and condenser fans. As such, there are no separate input variables or output variables available for the compressor or condenser fan. The only output variable available for reporting in EnergyPlus is the DX coil electricity consumption which includes compressor plus condenser fan.

Weather Data

The typical meteorological yeat (TMY) weather files provided as part of the HVAC BESTEST package are not directly usable by EnergyPlus. In order to

create an EnergyPlus compatible weather file, the TMY file was first converted to BLAST format using the BLAST weather processor (WIFE). An EnergyPlus translator was then used to convert the weather data from the BLAST format to EnergyPlus format.

RESULTS OF TESTING DURING INITIAL ENERGYPLUS DEVELOPMENT

HVAC BESTEST was first modeled using a beta version of EnergyPlus. This section discusses issues which arose during this phase of testing. Four separate rounds of official results were submitted to the IEA HVAC BESTEST group. Each round of tests is discussed below. Figures 1 through 6 show selected results illustrating the issues which arose during this testing.

Round 1 – EnergyPlus Beta 5 Build 007

During the first round of simulations several potential software errors were identified in EnergyPlus Beta Version 5-07:

- Fan electrical power and fan heat were consistently low compared to the analytical results for all tests.
- The reported cooling coil loads were consistently too high and apparently had not been adjusted for the fraction of the time step that the equipment operated, however, the DX coil electricity consumption and actual load delivered to the space were being adjusted appropriately for cycling time.
- For the dry coil cases, the reported sensible coil load was slightly higher than the reported total coil load. Latent load was not available as an output variable, but was calculated by subtracting the sensible from the total. This error caused small negative latent loads to be calculated for the dry coil cases.
- Zone relative humidity was higher for many tests compared to the analytical results, especially for the tests with wet coils. This difference was probably due to simulating a blow-thru configuration rather than the required draw-thru configuration.

Software change requests were posted. Once a new version became available, the tests were rerun.

Round 2 – EnergyPlus Beta 5 Build 014

EnergyPlus Beta 5-14 included changes to fix the following problems which were identified in HVAC BESTEST Round 1:

- Reporting of cooling coil loads were corrected to account for run time during cycling operation.
- The methods of calculating sensible heat ratio (SHR) and coil bypass factor were modified to eliminate the problem where the dry coil cases reported sensible coil loads which were slightly higher than the reported total coil loads. This error was causing small negative latent loads to be calculated for the dry coil cases.

During the second round of simulations with EnergyPlus Beta 5-14 the cooling coil error identified during the first round of simulations was corrected to account for cycling during each time step, and this brought the evaporator coil loads closer to the range of results for the other programs; but the loads were still higher than they should be. Another potential error was therefore identified which may have been masked by the coil problem identified in Round 1:

- Although there was excellent agreement for zone total cooling load, the evaporator cooling coil load was larger than the zone cooling load plus fan heat.
- Also, the mean indoor dry bulb for Case E200 moved from 26.7C to 27.1C.
- The other problems identified in Round 1 still remained (low fan power, poor agreement in zone humidity ratio).

Round 3 – EnergyPlus Version 1.0.0.011

The suite of HVAC BESTEST cases were simulated again using EnergyPlus Version 1.0.0.011 (the first public release of Version 1.0, April 2001), which included the following changes, made since Round 2:

- Modified method for calculating coil outlet conditions.
- Changed to use of double precision throughout all of EnergyPlus. (This change was prompted by various issues not related to HVAC BESTEST.)
- Added two output variables for tracking fan and compressor run time.
- Added an output variable for coil latent load.
- Added Draw-Thru Fan option to Window Air Conditioner model.
- The name of the DX coil object was changed from COIL:DX:DOE2 to COIL:DX:BF-Empirical to better represent its algorithmic basis.

In addition, the following input file changes were made:

- Changed from blow-thru fan to draw-thru configuration.
- Updated the DX coil object name to COIL:DX:BF-Empirical.

The following changes in results were observed:

- Indoor fan power consumption and fan heat decreased significantly from Round 2, moving farther below the analytical results.
- Space cooling electricity consumption changed slightly from Round 2 and moved closer to the analytical results.
- Mean indoor humidity ratio decreased compared to Round 2, moving farther away from the analytical results for most of the dry coil cases and moving closer to the analytical results for the wet coil cases.
- Mean indoor dry bulb for Case E200 moved further out of range to 27.5C (the setpoint for this case is 26.7C).

In general, except for fan power, fan heat, and humidity ratio, the overall EnergyPlus Version 1.0.0.011 results compared much better to the HVAC BESTEST analytical results.

Round 4 – EnergyPlus Version 1.0.0.023

The suite of HVAC BESTEST cases was simulated again using EnergyPlus Version 1.0.0.023 (a maintenance release, June 2001), which included both input file and source code changes from Version 1.0.0.011.

Input file changes for Round 4:

- The equipment performance curves were refit from scratch using data from Table 1-6c of the HVAC BESTEST specification. Previously, the curve coefficients had been taken from DOE-2 input files developed by another modeler. The energy input ratio (EIR) curve required for the EnergyPlus DX Coil model is based on compressor input power plus outdoor condenser fan power, but the EIR curve fit done for DOE-2 applied only to the compressor input power.
- Relaxed the min/max limits of the performance curve independent variables (cooling coil entering wet bulb and condenser entering dry bulb) to allow extrapolation of cooling capacity as a function or temperature (CoolCapFT) and EIR as a function of temperature (EIRFT) outside the bounds of the equipment performance data given in the specification..
- The BESTEST cycling degradation factor (CDF) curve was determined based on net total capacities of the unit while the EnergyPlus DX Coil model requires that the part load curve be expressed on the basis of gross sensible capacities. A new CDF curve was developed which was intended to be on a gross capacity basis, but a later review of this curve showed an error in the derivation. Further review showed that there is really little difference between net part load and gross part load, so the revised curve was then removed and the original CDF curve was used.
- The CDF curve (part load curve) was applied to the indoor fan operation where previously there was no input available for this. This change also required using the FAN:SIMPLE:ONOFF object instead of FAN:SIMPLE:CONSTVOLUME which has been used previously.
- Added one week of infiltration to the beginning of the Case E120 run period to prevent overdrying of the zone during the simulation warmup period. (See the results discussion below for more details.)

Relevant source code changes from Version 1.0.0.011 to Version 1.0.0.023:

- Standard air conditions for converting volume flow to mass flow in the indoor fan calculations were changed. HVAC BESTEST specifies that the volume flow rate is for dry air at 20C. EnergyPlus was using a dry-bulb of 25C at the initial outdoor barometric pressure with a humidity ratio of 0.014 kg/kg, although the EnergyPlus documentation indicated 21C and 101325 Pa was being used. EnergyPlus now calculates the initial air mass flow based on dry air at 20C at the standard barometric pressure for the specified altitude, and the documentation reflects this change.
- The specific heat for air throughout the air-side HVAC simulation was changed from a dry c_p basis to a moist c_p basis. Previously, a mixture of dry and moist c_p had been used for various HVAC calculations.
- The heat of vaporization (h_{fg}) for converting a zone latent load into a load in the HVAC system was changed.
- A new input field was added to FAN:SIMPLE:ONOFF to allow a CDF curve (part load curve) to be applied to the indoor fan operation where previously part load adjustments could only be applied to the compressor and outdoor fan.
- Changed the moisture initialization to use the initial outdoor humidity ratio to initialize all HVAC air nodes.

The following changes in results were observed:

- The sensible and latent coil loads improved and now track very close to the analytical results.
- The mean indoor temperature for Case E200 improved and now, along with rest of the cases, matches exactly with the analytical results.
- The mean indoor humidity ratio tracks the analytical values better, especially for the wet coil cases. For Case E120 however, the

EnergyPlus humidity ratio (0.0038) was much less than the analytical value (0.0079). Introducing infiltration for the first week of January only and then turning infiltration off, eliminates this problem and gives a mean indoor humidity ratio for the month of February of 0.0081. Even though all nodes are initialized to the outdoor humidity ratio at the beginning of the simulation, conditions during the simulation warmup days overdry the zone for this case. Without the infiltration during the first week, there is no source of moisture to overcome the overdrying and establish the desired equilibrium.

- Indoor fan power consumption and fan heat match analytical results in most cases or are slightly less than analytical results.
- COP results changed but are still mixed. One problem may have to do with the basis of the CDF curve in BESTEST versus what EnergyPlus requires. The BESTEST CDF curve was determined based on net total capacities of the unit while the EnergyPlus DX Coil model requires that the part load curve be expressed on the basis of gross sensible capaciies.

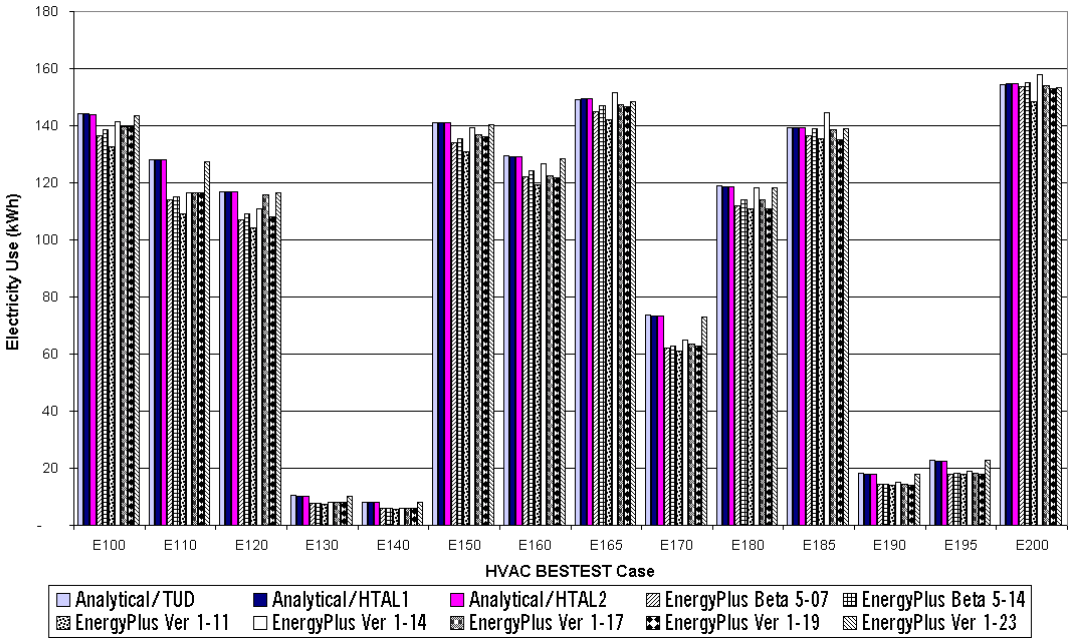

Figure 1 Indoor Fan Power Results for Early Versions of EnergyPlus

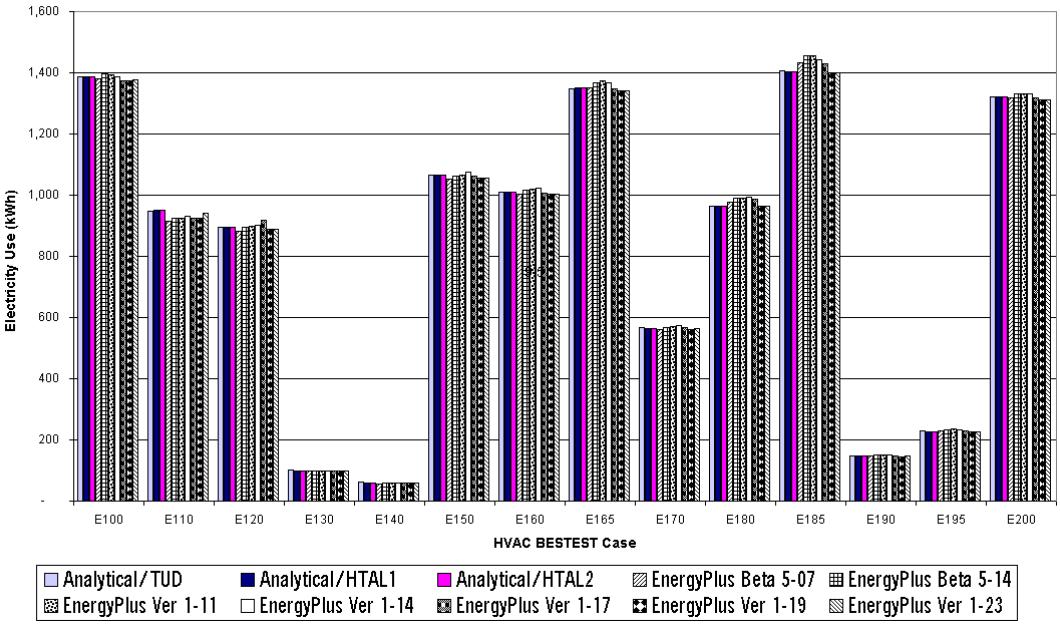

Figure 2 Compressor Plus Outdoor Fan Electricity Consumption Results for Early Versions of EnergyPlus

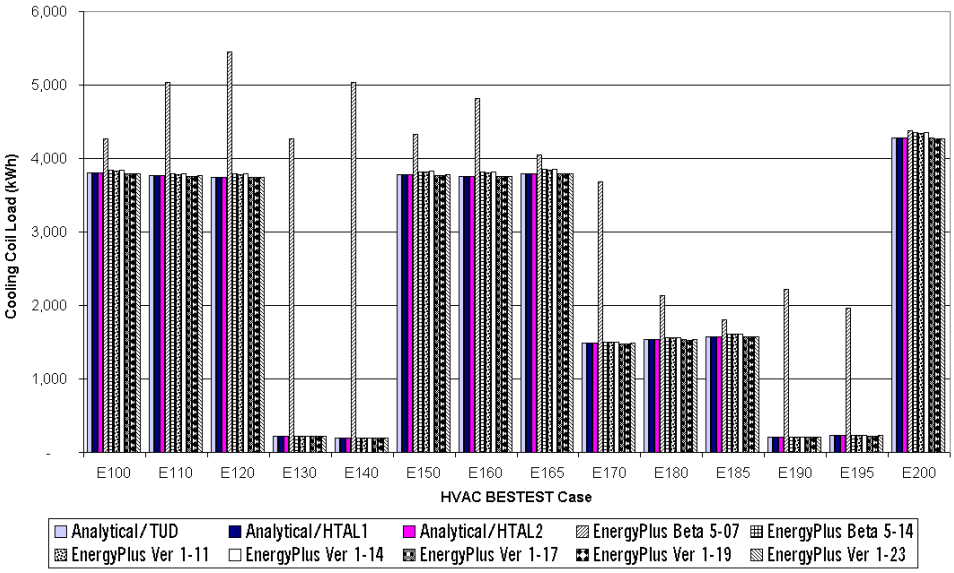

Figure 3 Sensible Cooling Coil Load Results for Early Versions of EnergyPlus

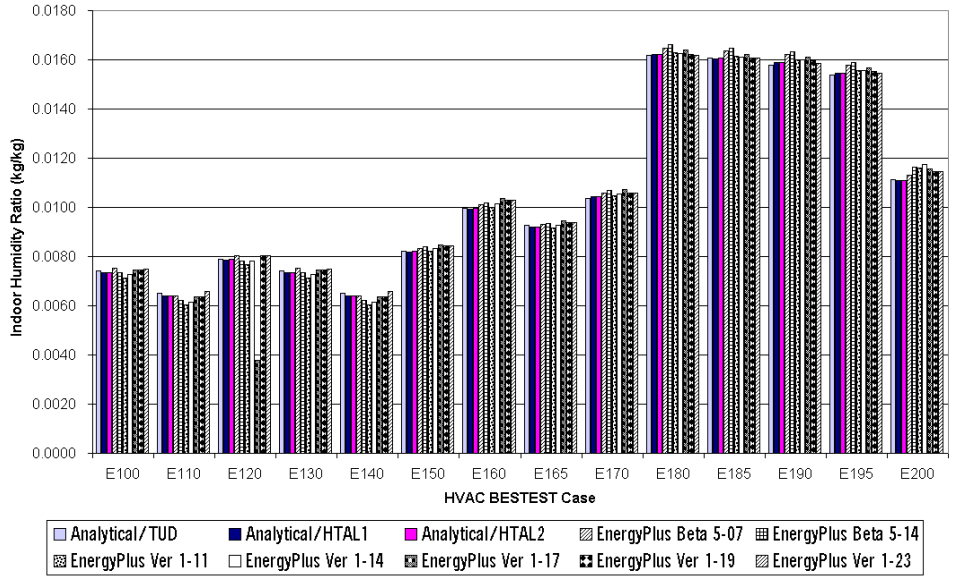

Figure 4 Latent Cooling Coil Load Results for Early Versions of EnergyPlus

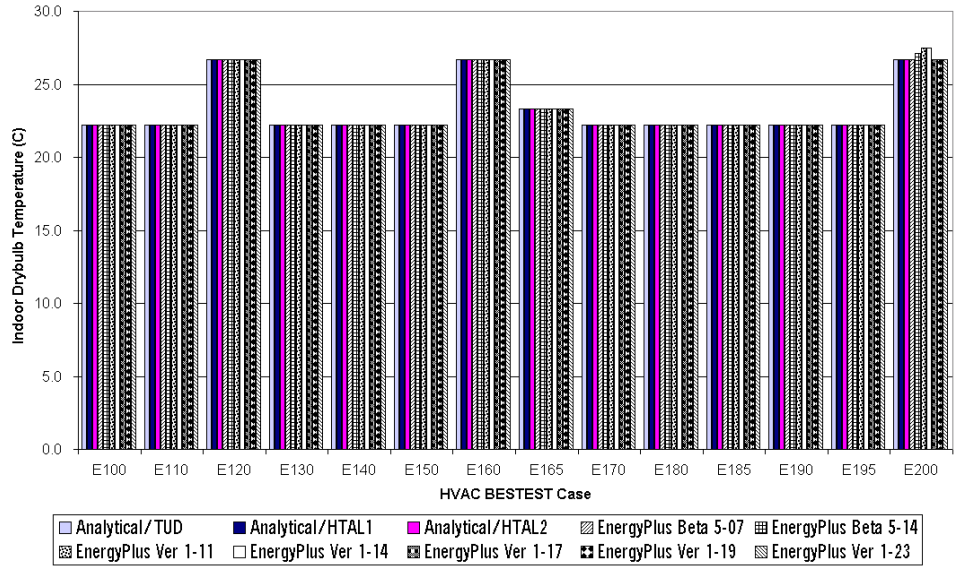

Figure 5 Indoor Dry-Bulb Temperature for Early Versions of EnergyPlus

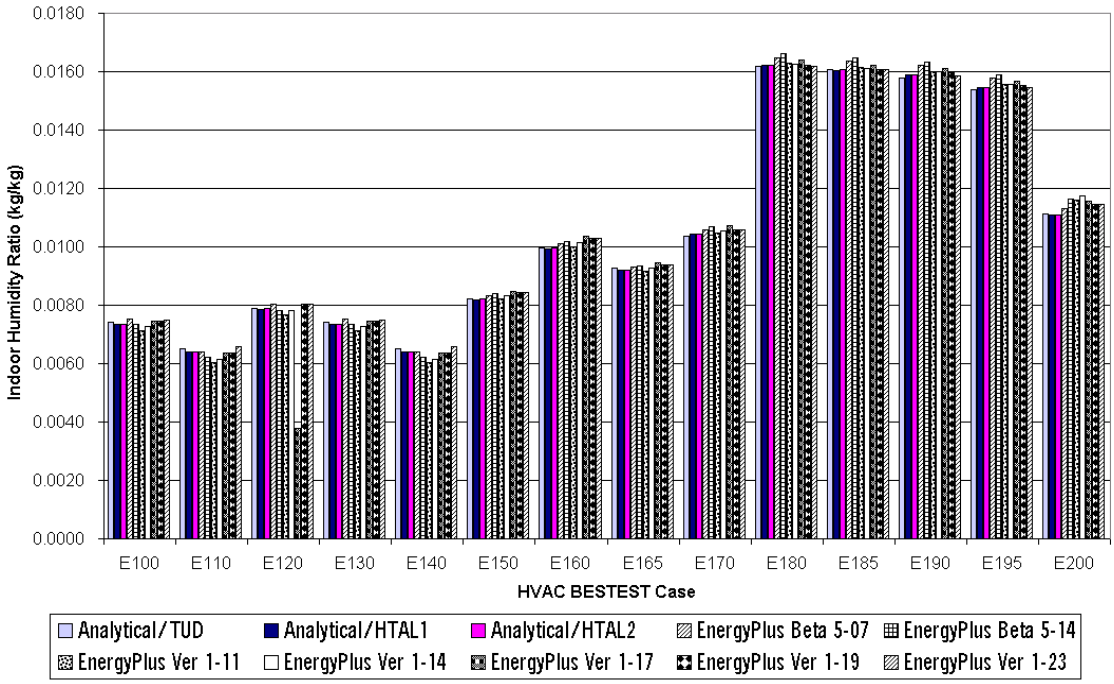

Figure 6 Indoor Humidity Ratio Results for Early Versions of EnergyPlus

RESULTS OF TESTING WITH SUBSEQUENT RELEASES OF ENERGYPLUS

The IEA HVAC BESTEST workgroup has completed their activities and final results are recorded in a report authored and released by NREL in January 2002 (Neymark & Judkoff 2002). Since the completion of that study, further capabilities and improvements have been added to EnergyPlus with new releases occurring in June 2002 (version 1.0.1), August 2002 (version 1.0.2) and December 2002 (version 1.0.3). The results for the HVAC BESTEST series with the three new releases of EnergyPlus along with the analytical results and results for the last test series reported in the IEA HVAC BESTEST final report (version 1-23) are presented in the charts below. Although some minor changes took place in version 1.0.2 and were later reversed in version 1.0.3, the results for version 1.0.3 Build 19 are identical to those for version 1-23. Pertinent changes implemented subsequent to version 1-23 were:

- Reformatted and changed the h_{fg} psychrometric function to conform with ASHRAE equations
- Added h_g psychrometric function as per ASHRAE equations and now use this for latent gain conversion to humidity ratio

Figure 7 shows the latent cooling coil loads for EnergyPlus release versions 1.0.0.023, 1.0.1.012, 1.0.2.008, and 1.0.3.019.

CONCLUSIONS

EnergyPlus Version 1.0.0.023 and subsequent versions up through the most recent release, EnergyPlus 1.0.3.019, was used to model a range of HVAC equipment load specifications as specified in *International Energy Agency Building Energy Simulation Test and Diagnostic Method for HVAC Equipment Models (HVAC BESTEST).* The ability of EnergyPlus to predict zone loads, cooling coil loads, cooling equipment energy consumption and resulting zone environment was tested using a test suite of 14 cases which included varying internal loads and outdoor conditions. The results predicted by EnergyPlus for 14 different cases were compared to results from 7 other whole building energy simulation programs that participated in an International Energy Agency (IEA) project which concluded in January 2002. Comparisons were also made with the results from three analytical solutions. EnergyPlus results generally agreed to within 1% of the analytical results except for the mean zone humidity ratio which agreed to within 3% for high SHR cases but was within 0.20% for low SHR cases. For more detailed results and discussion, see the EnergyPlus testing report for HVAC BESTEST E100 to E200 (Henninger and Witte, 2002).

The HVAC BESTEST suite is a very valuable testing tool which provides excellent benchmarks for testing HVAC system and equipment algorithms versus the results of other international building simulation programs. As discussed above, HVAC BESTEST allowed the developers of EnergyPlus to identify errors in algorithms and improve simulation accuracy. Acknowledgment

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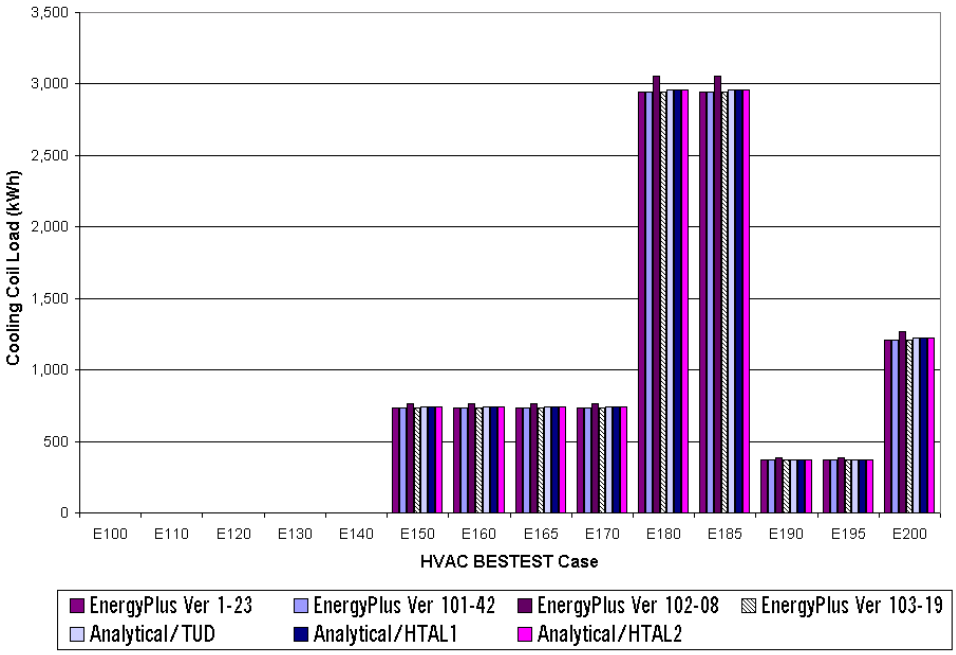

Figure 7 Latent Cooling Coil Load Results for Later Versions of EnergyPlus Note the increase in latent load in version 1.0.2.008 which was later corrected in version 1.0.3.019.